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Design and integration of Tokamak Coolant Systems based on water technology in the EU-DEMO

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ABSTRACT

The design of the primary heat transport systems is dependent on a multitude of requirements and constraints. Primarily, the thermal energy that is deposited in the first wall, blanket, divertor and limiters must be removed and transferred to the power conversion system at sufficiently high temperatures to achieve economically attractive efficiency. Additionally, the heat transport systems must provide a reliable barrier against radioactivity releases and be designed to ensure integrity throughout the plant lifetime. As such, safety considerations are critical from the early phases of the heat transport system's design as the minimisation of radiation exposure and plant activity levels must be pursued. The system design must cope with the contamination of the cooling water with activated products, and the transportation of these radiation sources outside the primary shielding by the coolant circulation. These activated products include strong gamma and neutron emitters. Finally, the significant operating temperature and pressure of the coolant results in high energy stored within the system. The integration concepts adopted to safely operate water coolant systems in a nuclear fusion device are outlined below. The design principles of EU-DEMO adopt the approach implemented in fission power plants, where the entire coolant system is integrated in building areas with massive concrete shielding and segregated from other plant systems. Furthermore, the building is adapted to withstand the consequences of an accidental release through the integration of a pressure suppression system. Finally, the coolant system is equipped with purification systems to prevent the accumulation of tritium and activation products.

The DEMO Tokamak Coolant Systems

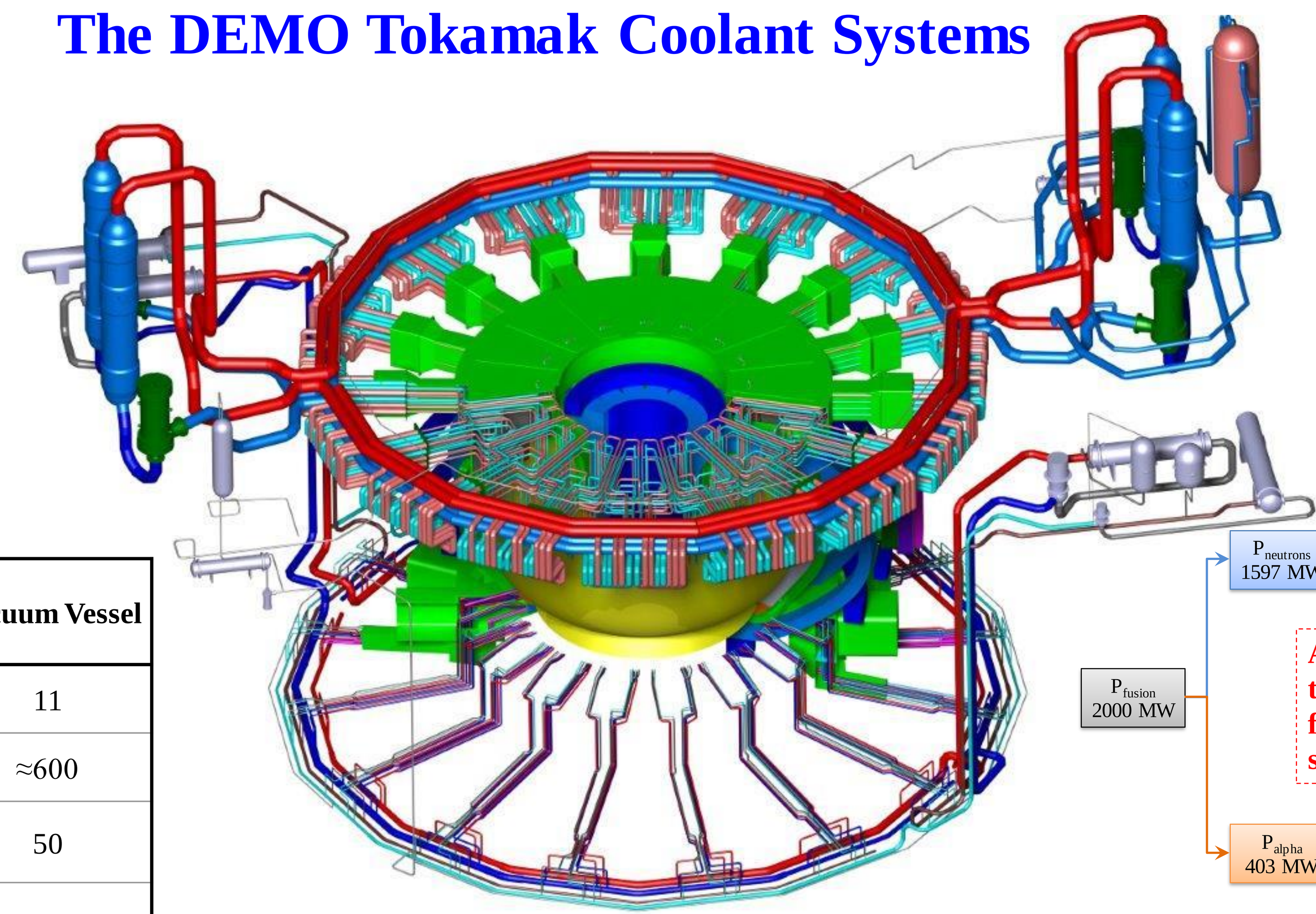
Separate heat removal systems operating at different pressure and temperature levels are utilized for:

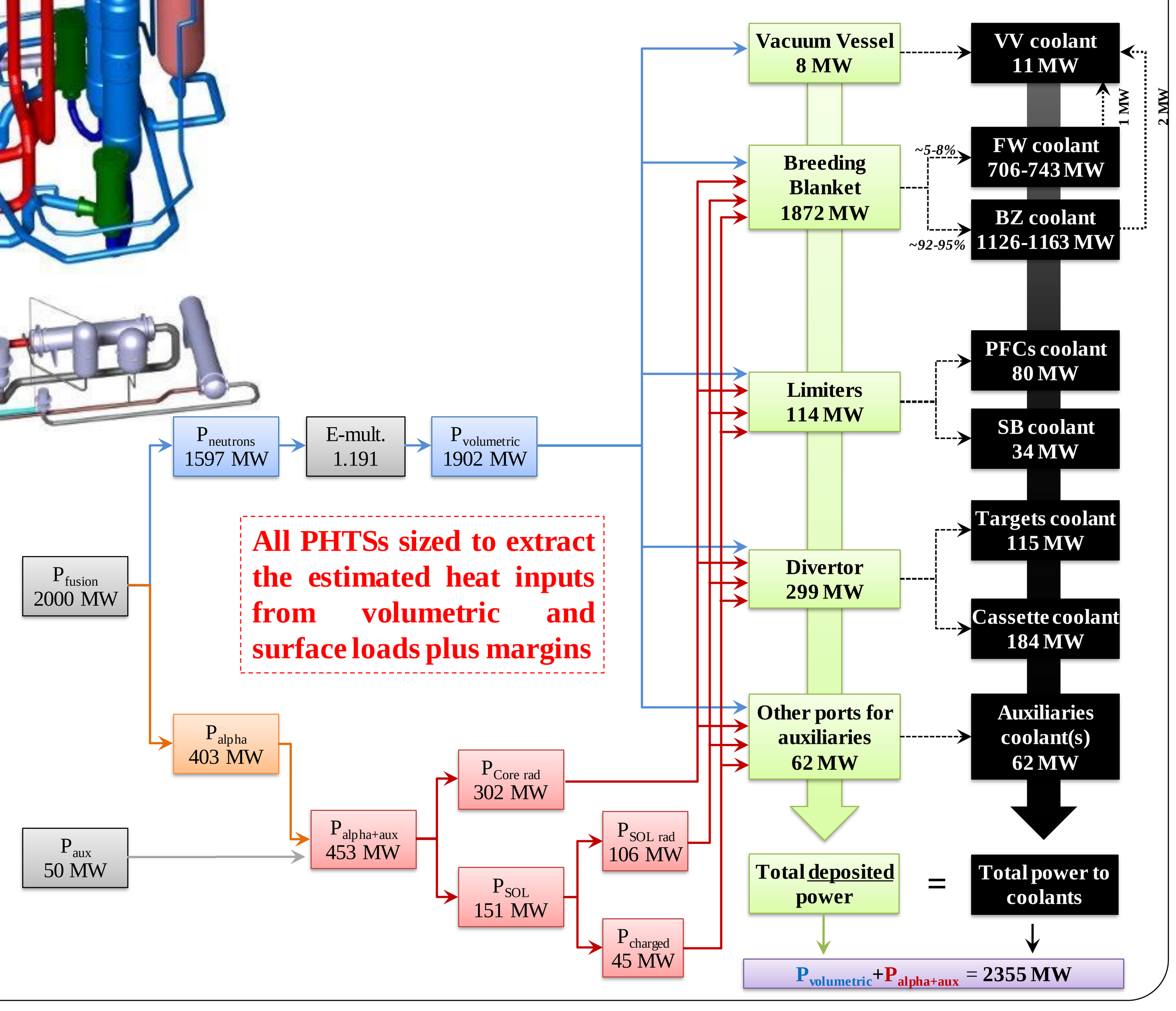
1) Breeding Blanket
2) Divertor Cassette and Limiters Shield Block
3) Divertor and Limiters Plasma Facing Components
4) Vacuum Vessel
5) Other auxiliaries (e.g., shield plugs, add. heating)

The first three sources integrated into energy conversion chain being judged economically attractive.
Heat from divertor and limiters exploited to preheat feedwater system. Thermal power from other sources is wasted.

Primary Heat Transport System	Breeding Blanket	Divertor cassette & Limiters shield	Divertor & Limiter PFCs	Vacuum Vessel
Nominal thermal-power [MW]	1900	230	240	11
Primary water volume [m³]	≈620	≈150	≈170	≈600
Primary temperature (ave) [°C]	311.5	195 (311.5)*	133	50
Primary pressure [MPa]	15.5	3.5 (15.5)*	5.0	1.4
Stored water energy [GJ]	530	100 (140)*	76 (90)**	75 (365)**

*An option with divertor cassette and limiters shield blocks at high temperature/pressure is being investigated
**Conditions refer to water baking at 180 °C





- **4 steam generators and 6 main heat exchangers**
- **10 main coolant pumps**
- **> 18 km of pipework with diameter up to DN 600, 53 mm thick**
- **≈ 40 MW of required power (<2% thermal power)**

Radiation protection approach

Radioactive contamination of water drives the integration in the building and systems design approach.

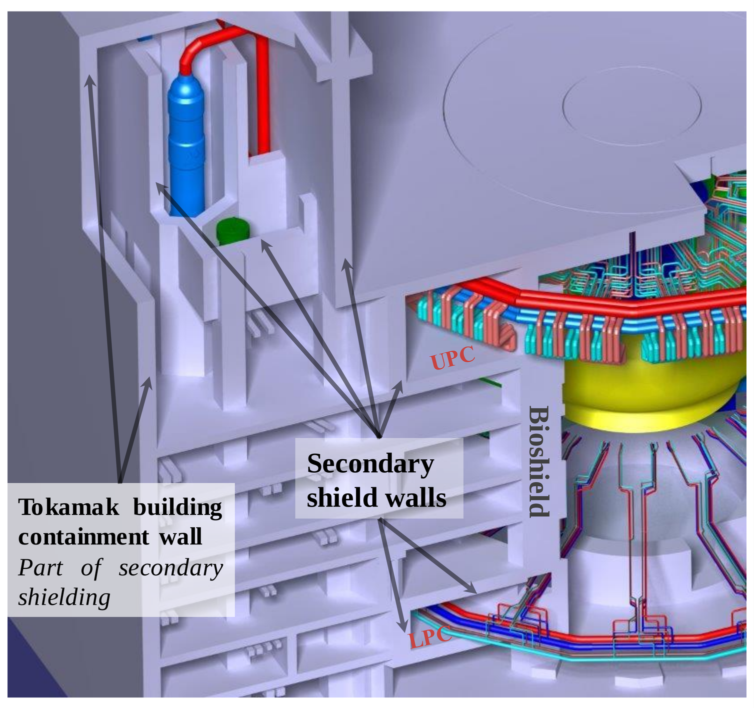
Main water activity [kBq g⁻¹]	DEMO – *2000 MW fusion power*			NPP
	BB PHTS	Divertor CB & Limiter SB PHTS	PFCs PHTS	AP600 *(1933 MW$_{th}$)*
^{16}N	4.38·10⁶	4.46·10⁶	8.40·10⁵	6.03·10³
^{17}N	6.06·10²	3.78·10²	1.17·10²	1.77
^{3}H	≤7.40·10⁴	<3.70·10⁴	<7.40·10⁴	1.3·10² *

*In CANDU 6 the ^{3}H concentration in HTS is typically limited to ≤9.25·10⁴ kBq g⁻¹

Long-term CRUD deposit specific activity [kBq g_{crud}^{-1}]	DEMO	NPP
	BB PHTS	AP600 *(1933 MW$_{th}$)*
^{58}Co	7.89·10⁴	4.44·10⁵
^{60}Co	1.61·10⁵	2.22·10⁵
^{59}Fe	2.22·10⁴	1.85·10⁴
^{54}Mn	1.31·10⁶	5.18·10⁴

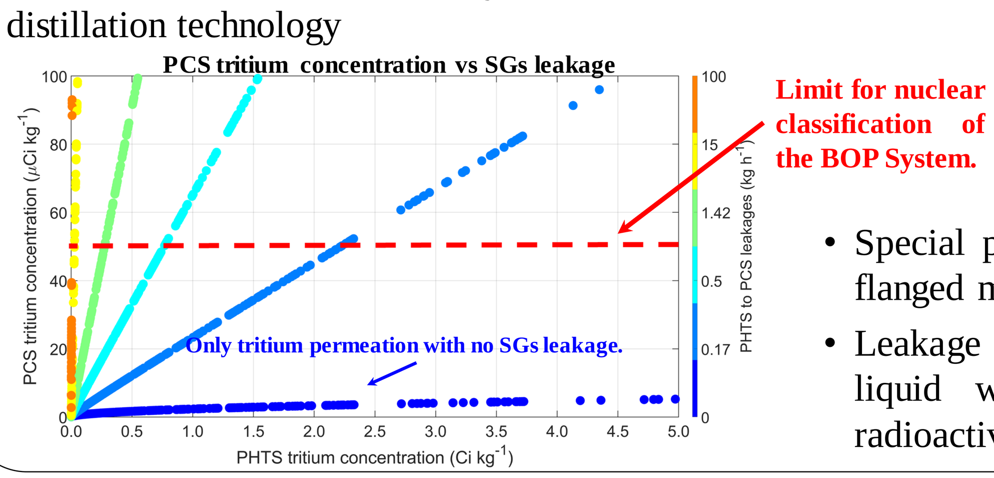
Secondary shielding requirements:

- **^{16}N** specific activity ~**700 times higher** than NPPs
- Secondary shielding in fission plants ~0.8-1.2 m
- Thicker walls to keep similar dose levels (+**50 cm**)



Water chemistry and purification:

- Tight control of water chemistry (pH, H_2, low halides contents, etc.) to minimize corrosion issue and radiation field
- **Purification half-life up to 60 min** to effectively remove corrosion products and ensure high water purity
- Dedicated **active detritiation system** for coolant based on water distillation technology



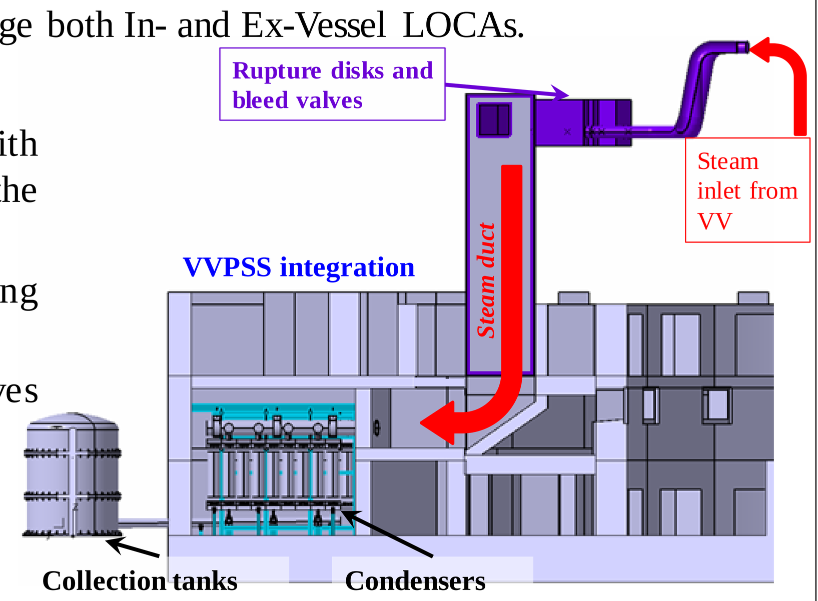
- Special provision to minimize and collect leakage from flanged mechanical joints, valve stems, pump shaft glands
- Leakage detections devices together with vapour and liquid water recovery systems keep under control radioactive discharge from stack

Suppression of pressure build-up during LOCA events

DEMO is equipped with pressure suppression systems to manage both In- and Ex-Vessel LOCAs.

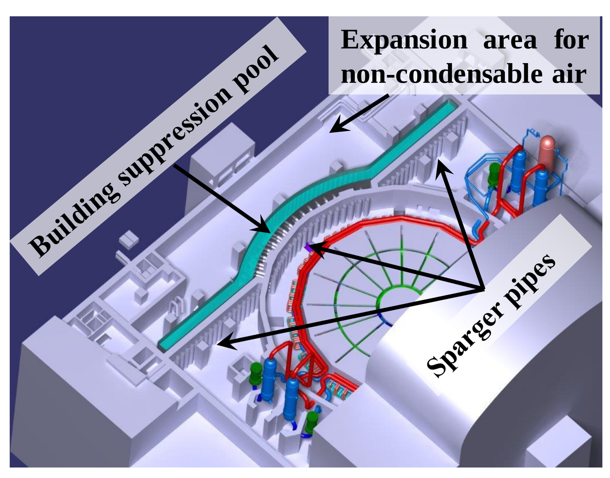
Vacuum Vessel Pressure Suppression System

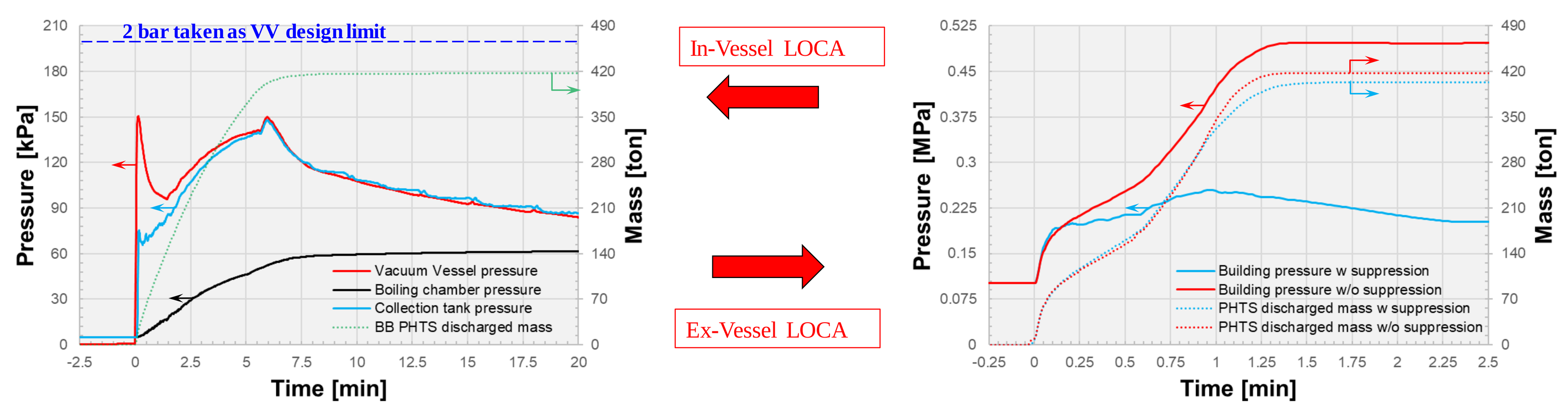
- Sized to accept the full discharge of water from the PHTS with the largest stored energy. Double-ended guillotine break of the largest feeder, DN200, considered as Design Basis Accident.
- **Fully-passive safety features**: natural circulation, and boiling and condensation phenomena are exploited.
- **6 rupture disks, 1 m each,** for large LOCAs, and bleed valves sized to handle small leaks, placed in dedicated area at L2.
- **11 m²** steel-lined duct connects L2 to B3 level
- Condensers heat transfer area ≥ **20000 m²**
- Inventory of water in the main pool ≥ **3500 m³**
- **Target for DBA**: peak pressure in the VV ≤**1.5 bar(a)**



Tokamk Building pressure suppression system

- Rooms housing the cooling systems are about 10⁵ m³. However this expansion volume alone is not sufficient to keep pressure below 2.5 bar(a) following a large Ex-VV LOCA.
- Suppression pool with **1700 m³ cold water** and spray systems are being integrated into the containment to mitigate pressure build-up and not to challenge the structural integrity of the second confinement barrier.





Conclusion and outlook

As result of the recent EUROfusion activities, requirements and constraints with the highest impact on PHTSs' integration within the tokamak building were identified. Relevant quantities associated to the main hazards implying systems operation were assessed as well. Analyses on PHTSs response during off-normal and accidental events are ongoing to assess design and safety implications of the engineering solutions that are currently under investigations.

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